MICROWAVE INSTABILITY AND ENERGY SPREAD MEASUREMENT VIA VERTICAL DISPERSION BUMP IN PETRA III

Y. Chae†, J. Keil, G. Sahoo, R. Wanzenberg, M. Ebert, A. Novokshonov, G. Kube, G.Falkenberg, M.Sprung, D. Dzhigaev, F. Westermeie, DESY, Hamburg, Germany

Abstract

The recent measurement of bunch length versus current indicated that the longitudinal impedance (Z/n) is 0.15 Ohm in close agreement with the impedance model [1]. Naïve application of Keil-Schnell criteria predicts that the threshold of microwave instability at 0.25 mA. Since the single bunch intensity is in the range of 0.2 – 2.5 mA depending on the fill pattern of PETRA III, we expect to observe the fill-pattern dependent energy spread according to the theory. However, the 3rd generation light sources comparable to PETRA III often reported the observation which was much greater than the theoretical one. In order to induce the beam size variation we had used skew quadrupoles to generate the dispersion in vertical plane. In particular we made dispersion bump at the undulator sector so that we were able to use the x-ray optics for the precise determination of small vertical beam size. In this paper we report the experimental setup and measurement data with the estimate on the instability threshold. We also report the vertical emittance and energy spread based on the x-ray beam size measurement as well as the rf signal which was excited by the beam at the longitudinal feedback cavity.

INTRODUCTION

One of the fundamental beam parameter in synchrotron light source is the energy spread, which is uniquely determined by the magnetic lattice of storage ring. The theoretical value in PETRA III is 0.1% (rms) at low current. Since the energy spread adds the width of the undulator's spectral lines, its increase will reduce the spectral brightness [2, 3]. Because of this reason we like to keep its value as small as possible regardless of fill pattern.

However, the precise determination of energy spread is not trivial in the light sources where the dispersion is very small at source points. The beam size measured by radiation monitor is then dominated by emittance, thereby losing its sensitivity to energy variation. In order to overcome the small dispersion at the source point the lattice was modified at the Advanced Photon Source to make a horizontal dispersion bump at one of the insertion device (ID) sector [4]. Even though the enlarged beam size augmented by the large dispersion was sufficient to detect the small energy variation due to microwave instability, the installation of new lattice was time consuming and it was very hard to change the value of dispersion.

In PETRA III the natural emittance is 1.2 nm and its emittance coupling is about 1%. The small vertical emittance makes its beam size at ID very small to be about 7 µm. This implies that we can achieve sufficient sensitivity in energy with the vertical dispersion as small as 7 mm. Even though this situation is not unique but true for all light sources, PETRA III has operated skew quadrupoles to control the vertical dispersion at ID sectors as part of user operations. Previous experience showed that we can easily raise the vertical dispersion above 20 mm in controlled way. This level of dispersion will make energy spread beam size 20 µm which is much larger than the one by vertical emittance. Hence, if we were able to measure electron beam size of 7 µm, we can accurately determine the energy spread of single bunch.

If we observe the increase in the energy spread as we increase the charge in a bunch, then we detect the microwave instability caused by the longitudinal impedance of the ring. If not, this experiment constitutes an accurate beam energy spread measurement of PETRA III. For the successful measurement the source size measurement by x-ray beamline is crucial.

The paper describes the controlled way of setting up dispersion bump at ID sectors. The method determining the vertical source size was described in detail. Finally, the estimate on energy spread was presented as the main result of this paper.

DISPERSION BUMP

PETRA III uses 20 damping wigglers to reduce the natural emittance from approximately 5 nm with damping wigglers open down to 1.2 nm with damping wigglers closed. Due to the strong field of the wiggler magnets of 1.5 T the dispersion functions have to be sufficiently small in both planes in the wiggler straight section and also in the double-bend achromat (DBA) arc. Otherwise the emittance will even increase instead of being reduced.

For the correction of the vertical dispersion in the three sections 12 skew quadrupoles are available in the vertical plane. For each section four skew quadrupole magnets are available. Two pairs with a phase advance of 90 degree are installed up- and downstream of the section at a place where there is sufficient horizontal dispersion. By coupling a fraction of the horizontal dispersion in the vertical plane it is possible to correct locally the dispersion to zero [5].

For this measurement the four skew quadrupoles in the DBA arc and the extension hall East have been used to increase the vertical dispersion intentionally at one beam line instead of reducing it. A vertical dispersion bump was

† yong-chul.chae@desy.de

computed which has the desired value and slope at one of the source points of the ID. Theoretical dispersion bump set at the user station P10 is shown in Fig. 1.

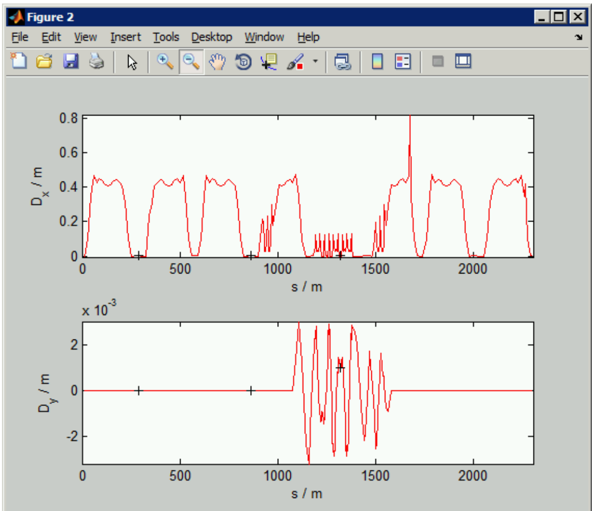

Figure 1: Theoretical horizontal dispersion (top) and vertical dispersion (bottom). The black cross indicates the source point whose X-ray image was taken for the measurement of electron beam size.

VERTICAL SOURCE SIZE

We designed the experiment to measure the beam size by using the X-ray beam lines of user stations. In order to increase the accuracy of measurement we took a pair of data for each current, namely, one at the vertical dispersion set to zero and the other at the vertical dispersion set to 20 mm. We always measured the dispersion first before beam line scientists took the data measuring vertical beam size. The measurements were performed at bunch currents from 0.25 mA to 2.5 mA, which encompasses both multi-bunch mode and timing mode. The experiment was carried out with the multiple bunches whose total current is maintained at 20 mA regardless of single bunch current level so that the heat load to the beamline instrument was the same during the experiment.

P10 Measurement

We selected an X-ray energy of 8 keV with its wavelength λ = 0.155 nm. A focusing lens is located at 71.5 m from the ID source (we denote this distance as *p*). The X-ray beam was focused to the knife edge position at 16.3 m behind the lens (we denote this distance as *q*). This is a *q:p=1:4.38* configuration. The vertical beam size before the lens was defined by a slit with the aperture size D = 0.30 mm. The measured focus size (σ_{meas}) can be normally approximated as an arithmetic sum of a demagnified source size (σ_{geom}) and an additional term added by the limited numerical aperture of the lens (σ_{diff}), namely,

$$\sigma_{meas}^2=\sigma_{geom}^2+\sigma_{diff}^2 \,. \qquad (1)$$

Once we obtained the demagnified source size then we can determine the source size of interest (σ_{source}) by using the relation:

$$\sigma_{source}=\sigma_{geom}\times\frac{p}{q} \,. \qquad (2)$$

The intensity of Fraunhofer diffraction pattern is approximated as a Gaussian profile whose rms size is:

$$\sigma_{diff}=0.45\frac{\lambda q}{D}=3.79\ \mu m \,. \qquad (3)$$

However, we find that we need an additional pre-factor of 0.69-0.74 to reduce the estimated diffraction beam size σ_{diff}. The reason for this correction is that the monochromator (located at 38.5m downstream of ID source) acts as a secondary vertical focusing element. Nevertheless, the optics was constant during the measurements. A summary of P10 results is shown in Table 1. All beam size values are FWHM in microns and averaged over at least three measurements. We had used the pre-factor set to 0.69 for this experiment which resulted in σ_{diff} (FWHM) = 6.14 µm, a constant for all data.

Table 1: FWHM Beam Size Measurement Data

I_b	Dispersion (set)	σ_{meas}	σ_{geom}	σ_{source}
mA	mm	µm	µm	µm
0.50	0	7.31	3.96	17.37
0.50	10	10.10	8.01	35.16
2.50	0	7.61	4.49	19.70
2.50	10	10.13	8.05	35.33
2.50	20	15.37	14.09	61.80
0.25	0	7.32	3.98	17.45
0.25	20	14.53	13.17	57.76
1.00	0	7.44	4.20	18.40
1.00	20	15.32	14.03	61.56
2.00	0	7.53	4.35	19.10

ESTIMATE OF ENERGY SPREAD

We analysed the data in Table 1 to estimate the energy spread as a function of current. The source size consists of two contributions from emittance and energy spread viz

$$\sigma_{source}=\sqrt{\sigma_\beta^2+\left(\eta\delta_p\right)^2} \,, \qquad (4)$$

where σ_β is the emittance part, η is the dispersion of source point, δ_p is the energy spread. The first estimate of σ_β is obtained as the beam size at zero dispersion as shown in Fig. 2 (we converted the data in Table 1 to rms values). The linear fit result indicates that the value of σ_β is 7.08 µm (rms). Since the vertical beta function is 3.95 m at the source point, the corresponding emittance is 12.7 pm which is in good agreement with PETRA III design value.

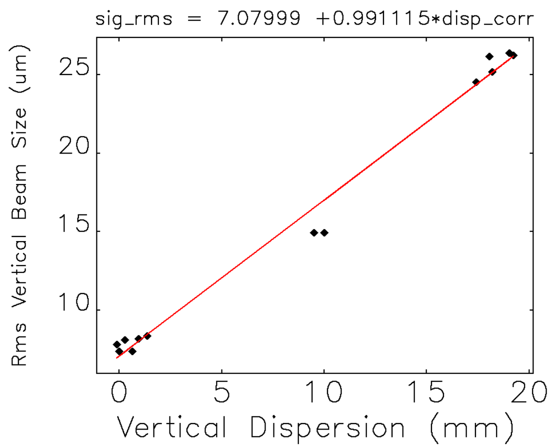

Figure 2: The vertical beam size (rms) as a function of the measured dispersion at the source point. The linear fit is used to estimate the σ_β.

By using Eq. (4) with the measured σ_β, we determined the energy spread (rms) as a function of current whose result is shown in Fig. 3. Since the microwave instability will increase the energy spread above the threshold current, our measurement showed that the operation mode of PETRA III is free of instability. The average of measurement is $<\delta_p>=0.131\%$ (rms) which is slightly greater than the design value of 0.1% (rms). Since the design value was obtained for the bare lattice without undulator magnet effects, we may attribute the increase to six undulators whose gaps were closed during the experiment.

As the second estimate we used more direct method to estimate the energy spread. Since we designed the experiment to measure the source size with vertical dispersion set at two values η_1 and η_2 for each current, we can easily extract the energy spread as

$$\delta_p = \sigma_2^2 - \sigma_1^2 / \eta_2^2 - \eta_1^2, \quad (5)$$

where σ_1 and σ_2 are the beam size measured at η_1 and η_1, respectively. The result was essentially the same as the first estimate, whose average is $<\delta_p>=0.131\%$ (rms).

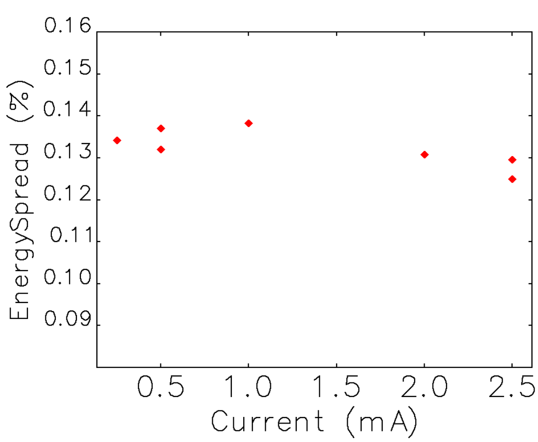

Figure 3: Energy spread (rms) as a function of bunch current, which shows no increase up to 2.5 mA.

P6 Measurement

We showed another example of measurement data, where about 1:1 focusing was used after a slit. The projected profiles are shown in Fig. 4, where a narrow group of solid curves represents the dispersion set to zero at P10 and a wide group of curves represents the dispersion set to 20 mm at P10. Each curve represents the profile of one current so that the data showed no significant variation in width for all currents. At P6 the dispersion was not measured, hence we did not use this data for determining the energy spread other than confirming no blow-up in beam size up to 2.5 mA.

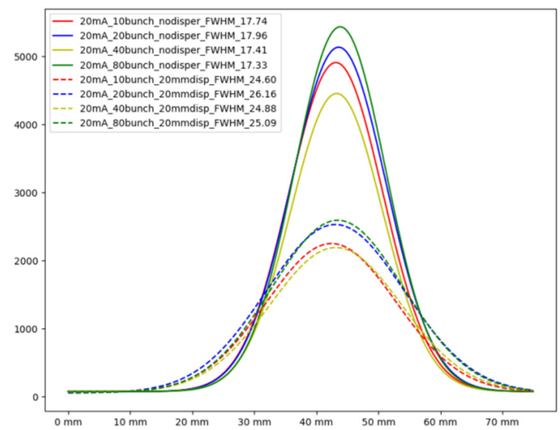

Figure 4: Vertical bunch profile with dispersion set to zero (solid curve) and set to 20 mm at the ID source point.

CONCLUSION

We had measured the energy spread of PETRA III storage ring by using hard X-rays from undulators to determine the vertical beam size. The vertical dispersion bump at the source point P10 was used to extract the energy spread out of the measured beam size. We determined the energy spread of the ring to be 0.131%. We did not observe the increase in the energy spread up to 2.5 mA of the single bunch current.

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